

613772
P.17

Resubmitted ApJ: May 10, 2002

THE ZODIACAL EMISSION SPECTRUM AS DETERMINED BY *COBE* AND ITS IMPLICATIONS

D. J. Fixsen¹ & Eli Dwek²

ABSTRACT

We combine observations from the DIRBE and FIRAS instruments on the *COBE* satellite to derive an annually-averaged spectrum of the zodiacal cloud in the 10 to 1000 μm wavelength region. The spectrum exhibits a break at $\sim 150 \mu\text{m}$ which indicates a sharp break in the dust size distribution at a radius of about 30 μm . The spectrum can be fit with a single blackbody with a λ^{-2} emissivity law beyond 150 μm and a temperature of 240 K. We also used a more realistic characterization of the cloud to fit the spectrum, including a distribution of dust temperatures, representing different dust compositions and distances from the sun, as well as a realistic representation of the spatial distribution of the dust. We show that amorphous carbon and silicate dust with respective temperatures of 280 and 274 K at 1 AU, and size distributions with a break at grain radii of 14 and 32 μm , can provide a good fit to the average zodiacal dust spectrum. The total mass of the zodiacal cloud is 2 to 11 E_{g} ($E_{\text{g}}=10^{18} \text{ g}$), depending on the grain composition.

The lifetime of the cloud, against particle loss by Poynting-Robertson drag and the effects of solar wind, is about 10^5 yr . The required replenishment rate is $\sim 10^{14} \text{ g yr}^{-1}$. If this is provided by asteroid belt alone, the asteroids lifetime would be $\sim 3 \times 10^{10} \text{ yr}$. But comets and Kuiper belt objects may also contribute to the zodiacal cloud.

Subject headings: Zodiacal Dust: Far Infrared Emission — Zodiacal Dust: observations

1. INTRODUCTION

The zodiacal dust (ZD) cloud consists of a population of micron to millimeter size particles sparsely distributed between the sun and the orbit of the asteroid belt. Its existence was known to the ancient Greeks as a faint band of light circling the sky along the ecliptic. In addition to

¹SSAI, Code 685, NASA/Goddard Space Flight Center, Greenbelt, MD 20771. e-mail: fixsen@stars.gsfc.nasa.gov

²Code 685, Laboratory for Astronomy & Solar Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771. e-mail: eli.dwek@gsfc.nasa.gov

reflecting sunlight, ZD particles emit their own thermal infrared (IR) spectrum after absorbing light from the sun. The first detailed mapping of the IR emission from the ZD cloud was performed by the *Infrared Astronomical Satellite (IRAS)* (Hauser et al. 1984, Clarke et al. 1993, Vrtilik & Hauser 1995). The search for an isotropic cosmic infrared background by the Diffuse Infrared Background Experiment (DIRBE) instrument on board the *Cosmic Background Explorer COBE* satellite required the careful removal of foreground emission generated by interplanetary dust particles, Galactic stars and interstellar dust from the diffuse sky. A byproduct of the DIRBE survey was therefore the derivation of the spatially varying zodiacal dust spectrum in the 1.25 to 240 μm wavelength range (Kelsall et al. 1998). These observations have led to the discovery of the complex geometrical nature of the ZD cloud, which consists of a main smooth cloud of particles slightly tilted with respect to the ecliptic plane, three sets of narrow dust bands (Reach et al. 1997), and a circumsolar ring with a trailing blob at 1 AU. Kelsall et al. (1998) describe in detail the ZD cloud components and refer to the original discovery papers. By fitting the brightness variations of the reflected and thermal light emission in the 10 DIRBE bands spanning the 1.25 to 240 μm wavelength range, Kelsall et al. (1998) derived a parametrized model of the three dimensional dust distribution, the temperature at 1 AU ($1 \text{ AU} = 1.5 \times 10^{11} \text{ m}$), and the albedo, phase function, and thermal emissivity of the various cloud components.

In this paper we present the 10 to 1000 μm thermal spectrum of the zodiacal dust cloud which was derived by combining the DIRBE observations with those obtained by the Far Infrared Absolute Spectrophotometer (FIRAS) instrument on the *COBE*. The spectrum, derived in §2, can be represented by a $\sim 240 \text{ K}$ blackbody at the shortest wavelengths, but shows a marked decrease in its emissivity at wavelengths longer than $\sim 150 \mu\text{m}$. Assuming that the IR emission arises predominantly from the main ZD cloud we use its geometrical properties to derive the size distribution and mass of its constituent particles (§3). We find that the size distribution of the ZD particles exhibits a sharp cutoff at a radius between 15 and $45 \mu\text{m}$, depending on the cloud composition. Particles of this size are continuously being lost in the system by Poynting–Robertson drag and momentum exchange with the solar wind that causes them to spiral into the sun (Burns, Lamy, & Soter 1979). Sources of dust particles required to maintain the cloud include comets (Liou & Zook 1996, Cremonese et al. 1997) and collisions between larger bodies in the asteroid (Mann et al. 1996) or Kuiper belt (Liou et al. 1996). By calculating the lifetime of the particles in the main ZD cloud we calculate the required rate of dust injection, and compare it to the different dust sources (§4). The results are summarized in §5.

2. OBSERVATIONS

2.1. COBE Datasets

In this paper we consider the thermal emission spectrum ($\lambda \gtrsim 10 \mu\text{m}$) of the ZD cloud, constructed from data obtained by the DIRBE and FIRAS instruments on the *COBE* spacecraft.

The *COBE* was launched into a Sun-synchronous Earth orbit with its plane almost perpendicular to the sun direction. The FIRAS instrument had a 7° diameter field of view pointing along the spin axis, whereas the DIRBE had a $0.7^\circ \times 0.7^\circ$ field of view pointing 30° off axis. This configuration allowed the DIRBE instrument to measure the emission from the ZD cloud over a range of solar elongation. In order to create a composite ZD spectrum, we use the DIRBE 12, 25, 60, 100, 140, and $240\ \mu\text{m}$ passband data from Pass 3 (Hauser et al. 1997) to produce full sky maps at a 90° elongation angle to approximately match the Pass 4 observations of the FIRAS instrument (Brodbeck et al. 1997). The FIRAS and DIRBE data have been compared in the range of overlap (Fixsen et al. 1997) and were shown to agree within their overall calibration uncertainties. We convolved the DIRBE 90° elongation maps to the lower FIRAS resolution using a 7° beam developed to simulate the FIRAS data (Fixsen et al. 1997). This led to a composite sky spectrum consisting of the 6 DIRBE bands and 210 FIRAS frequency bins from 2 to $97\ \text{cm}^{-1}$. Some of the noisy high frequency bins were combined to give 200 FIRAS frequency bins.

2.2. CMB, CIB, ISM, and ZD Emission Spectra

In addition to the ZD, the major contributors to the sky brightness in the 10 to $1000\ \mu\text{m}$ wavelength region are the cosmic microwave background (CMB), the cosmic infrared background (CIB), and the Galactic interstellar medium (ISM). Determining the ZD spectrum therefore requires the subtraction of these emission components from the sky maps.

The CMB dominates the sky from $\sim 500\ \mu\text{m}$ to 5 cm, but its spatial structure and spectral form are quite simple. Following a detailed analysis of the FIRAS data (Fixsen et al. 1996) we removed a model consisting of a spatially uniform black body spectrum with a temperature of $T = 2.7275\ \text{K}$ (the final recalibration has not been applied to Pass 4 data) and a dipole component with $\delta T = 3.368\ \text{mK}$ from the sky maps. Any errors in the data caused by thermometry errors (Mather et al. 1999) are on the $30\ \mu\text{K}$ level and are negligible for studying the ZD cloud.

The sky maps from which the CMB has been subtracted can be written as a sum over emission components from the CIB, the ISM, and the ZD cloud, as:

$$\mathcal{D}^p(\lambda) = \sum_{c=1}^4 M_c^p S^c(\lambda) \quad (1)$$

where $\mathcal{D}^p(\lambda)$ is the map intensity at wavelength λ at pixel location p , M_c^p is the spatial template of the emission component c at pixel p , and $S^c(\lambda)$ is the spatially-independent spectral intensity of the c -component at λ .

The CIB was represented by a spatially uniform emission component. The ISM emission was represented by two components: the maps of C^+ and N^+ emission derived by Fixsen et al. (1998). These maps were found to be good tracers of the neutral and ionized gas phases of the ISM (Fixsen et al. 1996, 1998). In spite of the complexity of the ISM, this procedure was found to be

successful in separating the Galactic dust emission from other emission components (Fixsen et al. 1996, Hauser et al. 1998, Fixsen et al. 1998, Schlegel et al. 1998).

The spatial distribution of the ZD cloud was represented by the 240 μm map of the Zodiacal emission derived by Kelsall et al. (1998). The choice of wavelength was motivated by its overlap with the FIRAS spectrum, however, the use of other wavelengths yielded very similar results. This is the same process that was used to separate the cosmic background anisotropy from the foreground sources. Consequently, the results of the fit closely follow those of Kelsall et al. (1998) and Arendt et al. (1998) for the Zodiacal and Galactic emission respectively.

Equation (1) is invertible since its various components are a priori known to have distinct spatial and spectral signatures. The spectra S^c of the emission components c is given by:

$$S^c = [M_c^r G_{rq} M_\beta^q]^{-1} \cdot [M_\beta^s G_{sp} D^p] \quad (2)$$

where G is a suitable measure of the weight ($1/\sigma^2$) of the data when the errors in the map are correlated. A poor selection of G yields a noisy, but unbiased, set of spectra unless it is correlated with the errors in either D or M . We used the weights from Fixsen et al. (1997), and solved eq. (2) for each wavelength λ to derive the spectrum of each emission component.

The uncertainties in the FIRAS and DIRBE data are propagated into uncertainties in the zodiacal spectrum using eq. (2). The χ^2 of the fit is of order 1.2 per degree of freedom in line with the quality of fit from other FIRAS results. Uncertainties in the ISM ($\sim 1\%$), and ZD ($\sim 1\%$) template maps are not expected to affect the accuracy of the derived ZD spectrum.

The components of the fit are shown in Fig. 1. The C^+ and N^+ components have been combined to produce an average Galactic spectrum. These are the averages over the sky used in the fit which omits Galactic latitudes less than 9° . Of course, the Galactic emission is concentrated in the Galactic plane, and the Zodiacal emission is concentrated in the ecliptic plane. The uncertainty of the fit is reflected in the scatter from a smooth line. Note the spike in the Galactic spectrum at 158 μm is the C^+ emission line. The 206 μm N^+ emission line is also evident even though the Galactic plane is not used in this fit. The higher scatter in the short wavelength FIRAS data is a reflection of the lower transmission efficiency of the FIRAS instrument.

3. The Zodiacal Dust Cloud

3.1. General Characteristics of the Emission Spectrum

The CIB and ISM spectra we derived are similar to those presented by Hauser et al. (1998), Arendt et al. (1998), and Fixsen et al. (1996, 1998). The new aspect of our study is the 10 to 1000 μm spectrum of the ZD cloud which is shown in Fig. 2, normalized to that of a 240 K blackbody. The figure shows that at wavelengths below $\sim 150 \mu\text{m}$ the ZD spectrum is roughly

that of a 240 K blackbody with a gray emissivity of $\sim 3 \times 10^{-7}$, similar to the value of 10^{-7} quoted by Leinert (1996) for the optical depth of the zodiacal cloud. At wavelengths above $150 \mu\text{m}$, the emissivity becomes wavelength dependent, falling off as λ^{-2} .

In spite of its simplicity, this one-temperature fit to the ZD spectrum can be used to derive valuable information about the size distribution and mass of the main cloud. The temperature of the spectrum is lower than the value of 279 K expected for a blackbody at a distance of 1 AU from the sun. This suggests that a significant contribution to the spectrum arises from cooler dust at larger distances. Detailed Mie calculations show that the emissivity of a spherical dust particle is roughly unity at wavelengths shorter than $2\pi a$, where a is the radius of the particle, falling off as λ^{-n} , with $n \approx 1-2$, at longer wavelengths. From these general dust properties we can conclude that the ZD spectrum is dominated by emission from particles with radii smaller than $\sim 30 \mu\text{m}$. A large population of bigger particles will produce a gray blackbody spectrum that, normalized to that of a blackbody, will remain flat beyond $150 \mu\text{m}$, contrary to the observed λ^{-2} decline.

For an optically thin cloud, the emissivity of the graybody is equal to its optical depth. The optical depth can be written as $\tau = n_d \pi a^2 L$, where n_d is the number density of dust particles of radius a , and L is the Earth's distance to the edge of the cloud. Modeling the cloud as a simple cylinder of with a heliocentric radius $R = 3 \text{ AU}$ ($L = 2 \text{ AU}$) and height $h = 0.25 \text{ AU}$, and adopting a grain density $\rho = 3 \text{ g cm}^{-3}$ and radius $a = 30 \mu\text{m}$, gives a value of $M_z = \pi R^2 h n_d (4\pi \rho a^3/3) \approx 3 \times 10^{18} \text{ g}$, which is consistent with the mass derived with the more detailed model described below.

3.2. Detailed Modeling of the Zodiacal Dust Spectrum

The single temperature cylindrical representation of the ZD cloud properties is useful, but a clear oversimplification of the true nature of the spectrum and the spatial distribution of the dust. In a more realistic model, the observed IR brightness at frequency ν along any given line of sight through the ZD cloud is given by the double integral:

$$S_\nu(\nu, \theta, \phi) = \int \int n_0 K[\theta, \phi, R(s)] B_\nu[\nu, T(s)] \pi a^2 Q(\nu, a) f(a) da ds \quad (3)$$

where, R is the distance from the sun, s is the distance along the line of sight which is defined by θ , its angle above the ecliptic plane, and ϕ , the angle around the sun which is determined by the time of year, B_ν is the Planck function, $T(s)$ is the dust temperature at the point s along the line of sight, n_0 is the number density of dust particles in the plane of the ecliptic at distance of 1 AU from the sun, $f(a)$ is the grain size distribution normalized to unity, $Q(\nu, a)$ is the dust emissivity, and $K[\theta, \phi, R(s)]$ is the geometric form factor of the ZD cloud describing the variations in the number density of dust particles as a function of $\{\theta, \phi, s\}$. Of course eq. (3) can only be tested along lines of sight covered by the FIRAS survey, that is, those that are at right angles to the Sun-Earth vector, thus the relation between R and s is given by: $R \equiv R(s) = \sqrt{1 + s^2}$ (R, s in AU).

We used the smooth dust cloud as parametrized by Kelsall et al. to characterize the density distribution of the ZD cloud. Using the notation in Kelsall et al. :

$$K(\theta, \phi, R) = R^{-\alpha} e^{-\beta g^\gamma}$$

$$g = \begin{cases} \frac{(Z/R)^2}{2\mu} & \text{for } |Z/R| < \mu \\ |Z/R| - \mu/2 & \text{for } |Z/R| \geq \mu \end{cases} \quad (4)$$

where $Z = s \sin \theta$ is the height above the ecliptic plane. From Kelsall et al. (see the entries for the smooth cloud in Table 1 of their paper) $\alpha = 1.34$, $\beta = 4.14$, $\gamma = 0.942$, and $\mu = 0.189$. The eccentricity of the the Earth's orbit and the small offset of the cloud from the sun were ignored in our calculations.

The dust temperature, $T(s)$, at any position s along the line of sight is given by:

$$T(s) = T(0) \left(\frac{\bar{Q}_0}{\bar{Q}_s} \right)^{1/4} R^{-1/2} \quad (5)$$

where $T(0)$ is the dust temperature at 1 AU, and \bar{Q}_0 , and \bar{Q}_s are the Planck-averaged dust emissivities at temperatures $T(0)$ and $T(s)$, respectively. Figure 2 shows that the zodiacal spectrum deviates from that of a black body only at wavelengths longer than $\sim 100 \mu\text{m}$. So in practice, for dust temperatures above $\sim 100 \text{ K}$, $(\bar{Q}_0/\bar{Q}_s)^{1/4} \approx 1$, and the dust temperature decreases with distance as $R^{-1/2}$. This radial dependence is very close to the $R^{-0.47}$ decrease derived by Kelsall et al. From Fig. 2, less than 0.5% of the radiation is affected by the finite size of the particle, justifying the simplification that the dust temperature is independent of grain size.

The dust temperature at 1 AU, $T(0)$, was taken to be a free parameter, and it is fit as part of the model. Since the emission spectrum is a convolution of a Planck function and the dust emissivity, the best fitting value of $T(0)$ depends on the dust composition.

From the simple model depicted in Fig. 2, we know a priori that the dust spectrum has a sharp break at radii near $\sim 30 \mu\text{m}$. The ZD spectrum shows that large dust particles are rare compared to the number of particles at the break radius, however, the exact slope of their size distribution is difficult to determine since these large particles do not contribute significantly to the far IR emission. We therefore parametrized the grain size distribution as a double power law with a normalization constant f_0 , and a break at radius a_b of the form:

$$\begin{aligned} f(a)/f_0 &= (a/a_b)^{k_1} & a \leq a_b \\ &= (a/a_b)^{k_2} & a > a_b \end{aligned} \quad (6)$$

where the steep $k_2 = -5$ falloff at large grain radii was taken from Grün (1993).

The integrals of eq. (3) can then be performed separately, and the equation can be written as:

$$S_\nu(\nu, \theta, \phi) = n_0 \int K(\theta, \phi, R) A(\nu) B_\nu[\nu, T(R)] ds, \quad (7)$$

where $A(\nu)$ is a size-averaged cross section of dust at frequency ν , given by:

$$A(\nu) = \int m_d(a) \kappa(\nu, a) f(a) da, \quad (8)$$

where $m_d(a) = \frac{4}{3}\pi a^3 \rho$ is the mass of a dust particle, ρ is its mass density, $\kappa(\nu, a) = 3Q(\nu, a)/4\rho a$ is the mass absorption coefficient of the dust, where we have arbitrarily taken the limits of the grain size distribution from $a = 1 \mu\text{m}$ to 1 mm .

Finally the spectrum is averaged over the angles θ and ϕ to match the averaging of the data:

$$\langle S_\nu(\nu) \rangle = \frac{1}{4\pi} \int \int \int n_0 K(\theta, \phi, R) A_\nu B_\nu[\nu, T(R)] d\phi |\sin \theta| d\theta ds \quad (9)$$

The ZD particles are probably a mixture of carbonaceous dust, polycyclic aromatic hydrocarbons, silicates, ices, and metallic oxides. For computational purposes we have used a single composition for the cloud, taken to be graphite, amorphous carbon, or silicate. The optical constants were taken from Draine & Lee (1984) for graphite and silicates, and from Rouleau & Martin (1991) for amorphous carbon. For a given cloud composition, the average spectrum $\langle S_\nu(\nu) \rangle$ is a function of the model parameters $T(0)$, the dust temperature at 1 AU; a_b , the characteristic radius in the size distribution; k_1 , the index of the grain size distribution for $a < a_b$; and n_0 , the number density of the ZD cloud at 1 AU.

We found that the best fit to the observed spectrum was obtained for a dust cloud consisting of silicates as did Reach (1988) in looking at the shorter end of our wavelength range. That silicate may be the dominant IPD cloud constituent is also suggested by the presence of a broad emission hump in the 9–11 μm region observed with the *Infrared Space Observatory* satellite, which may be attributed to the 9.7 μm silicate feature (Reach 1997). For this composition we found that $T(0) = 274 \pm 10 \text{ K}$, $a_b = 32 \pm 2 \mu\text{m}$, $k_1 = -2.3 \pm 0.1$; and $n_0 = 2.2 \times 10^{-8} \text{ m}^{-3}$. Figure 3 depicts the grain size distribution, and Fig. 4 shows contours of the confidence level of the renormalized χ^2 of the fit for the different parameters. Figure 5 compares the model spectrum to the observations. Cloud parameters for all the different cloud compositions examined in this paper are summarized in Table 1.

The formal χ^2 was significantly improved with a steeper cutoff than measurements from Grün et al. would suggest at larger sizes. A steeper cutoff also changes the parameters of the fit.

The temperature, cutoff size and the mass of the ZD dust cloud are relatively stable under changes of composition and variations of k_2 , ranging from 260 to 300 K, 15 to 45 μm and 2 to 11 Eg, respectively. The index, k_1 , of the smaller particles changes sign for graphite. And the mean mass of a dust particle also shows strong dependence on the details of material.

Having determined the n_0 and the grain size distribution, the mass of the ZD cloud is obtained by an integration over its spatial density variations described by eq. (4). The total mass of the zodiacal dust cloud is thus given by the integral:

$$M_z = \int_a m(a) f(a) da \int_{V_{ol}} n_0 K(\theta, \phi, R) R^2 \sin \theta d\theta d\phi dR$$

$$\begin{aligned}
 &= n_0 \int_a m(a) f(a) da \int_0^\pi \int_0^{R_m} \int_0^{2\pi} R^{-\alpha} e^{-\beta g^\gamma} R^2 \sin \theta \, d\phi \, dR \, d\theta \\
 &= \frac{2\pi n_0 \langle m \rangle R_m^{3-\alpha}}{3-\alpha} \int_0^\pi e^{-\beta g^\gamma} \sin \theta \, d\theta
 \end{aligned} \tag{10}$$

The integral over the full 4π steradian of solid angle is straightforward, however, the integral over R depends on the radial dimension of the ZD cloud. Formally, the ZD spectrum was derived from lines of sights that sample the ZD cloud at distances $R > 1$ AU. However, its geometry was derived from DIRBE observations which sampled the cloud morphology down to distances of $R = 0.87$ AU. From the analysis of *Helios* data, Leinert et al. (1981) showed that the $R^{-1.3}$ behavior of the dust distribution extends down to a heliocentric distance of 0.3 AU. The integral in eq. (10) converges rapidly as $R \rightarrow 0$ so we adopted a lower limit of $R = 0$. However, without an upper limit on R the integral diverges. Since the asteroids may be a significant source of the dust, their location at ~ 3 AU is a natural cutoff for the outer limit of integration. The numerical value of the θ -integral of eq. (10) is:

$$\int_0^\pi e^{-\beta g^\gamma} \sin \theta \, d\theta = 0.618 \tag{11}$$

giving a mass of $M_z(g) = 14.5 n_0(\text{AU}^{-3}) \langle m \rangle$ for the smooth zodiacal dust cloud.

For a ZD cloud consisting of silicates $\langle m \rangle = 8$ ng giving $M_z = 8 \text{ Eg}$ ($= 8 \times 10^{18}$ g). For a cloud consisting of graphite or amorphous carbon $\langle m \rangle = 154$ and 6 ng, respectively, giving ZD cloud masses of 11 Eg and 3.4 Eg.

4. DISCUSSION

The major new results of this paper are the derivation of the average 10 to 1000 μm spectrum of the ZD cloud, its grain size distribution, and the total cloud mass.

Our results show that the size distribution has a sharp break at radii near 15–45 μm . This result depends weakly on the assumptions of the dust material, and was mainly determined from the fairly sharp $\sim 150 \mu\text{m}$ break in its spectrum. A similar model (Harper et al. 1984) was used to infer the size of the particles in the dust cloud around Vega from a spectrum with only a few frequencies and poorer signal to noise ratio.

The break in the size distribution occurs at $\sim 30 \mu\text{m}$ which for silicate dust ($\rho = 3 \text{ g cm}^{-3}$) corresponds to a dust mass of 3×10^{-7} g. This mass corresponds to the peak in the dust mass distribution derived by Grün et al. (1984) from *in situ* measurements of meteoroid penetration data obtained by spacecraft, and from studies of submicron lunar craters produced by IPD particles. This agreement is remarkable considering the fact that they were derived from totally different physical effects of the IPD cloud.

The details of the size distribution, as expressed by the indices of the power law for grain radii above and below the break, are less certain. The fall off in the number of large grains is too steep

to be determined from the *COBE* data, and the index of the power law for small grains is too dependent on the cloud composition to determine from this analysis. In spite of these uncertain details, the main conclusion, that the size distribution has a sharp break around $30\ \mu\text{m}$ is robust, and independent on the details of the cloud composition.

The temperature of the dust at 1 AU (260–300 K) brackets the 279 K attained by a blackbody placed at the same distance. A different temperature might be an indication that the visible absorption efficiency is different than that at infrared wavelengths. The ratio of the absorption (emission) efficiency at $\sim 0.5\ \mu\text{m}$ needs only to be between 75 to 125% of its value at $\sim 10\ \mu\text{m}$ to explain the different temperatures. Mie calculations for the dust constituents considered here suggest that $Q(0.5\ \mu\text{m})/Q(10\ \mu\text{m}) \approx 0.85$ to 1.09 , consistent with that required to explain the range of dust temperatures at 1 AU.

The total mass we derive for the ZD cloud depends mainly on its optical depth, geometry, and dust composition. The range of values we derive for the cloud mass reflect the different dust composition. The true mass of the cloud should lie within the derived limits, since the three different type of dust particles used in the model span a wide range of dust optical properties: $\kappa(30\ \mu\text{m}) \approx 60$ to $100\ \text{cm}^2\ \text{g}^{-1}$, and grain mass densities $\rho \approx 2$ to $3\ \text{g cm}^{-3}$.

The mass range we derive for the IPD cloud, $M_z \approx 2\text{--}11\ \text{Eg}$, is on the low side of the 10 to 100 Eg range quoted by Leinert (1996), but not inconsistent with his estimates considering the considerable uncertainties he ascribes to these values.

Micron-sized dust particles orbiting a star will have a finite lifetime due to the effects of Poynting–Robertson (PR) drag and solar wind effects. For $\sim 30\ \mu\text{m}$ size particles the PR drag dominates over the corpuscular drag (Burns, Lamy, & Soter 1979). For a particle mass density of $\rho = 3\ \text{g cm}^{-3}$, a grain radius of $30\ \mu\text{m}$, and a radiation pressure efficiency, $Q_{pr} = 0.5$, we get that the PR lifetime for a particle at 1 AU is about $10^5\ \text{yr}$. Since most of the IPD mass is in $\sim 30\ \mu\text{m}$ particles, the mass loss rate from the cloud is $\sim 6 \times 10^{18}/10^5 \sim 6 \times 10^{13}\ \text{g yr}^{-1}$. If this mass loss occurs in a volume given by a sun-centered cylinder with a radius of 3 AU and a height of 0.25 AU, then the mass loss rate is $\sim 9 \times 10^{-29}\ \text{g m}^{-3}\ \text{s}^{-1}$, in good agreement with that given by Grün et al. (1985).

To maintain a steady state, this mass loss rate must be matched by a dust production rate. Asteroids, having a total mass of $\sim 2 \times 10^{24}\ \text{g}$ (Cox 2000), can provide this mass rate for $\sim 3 \times 10^{10}\ \text{yr}$, longer than the lifetime of the solar system. Other sources, such as comets or Kuiper belt objects, can also be a source of interplanetary dust in the solar system.

Acknowledgements: DJF acknowledges the support of NASA Astrophysical Data Program S-92561-Z, and ED acknowledges the support of NASA’s Astrophysical Theory Program NRA 99-SS-01

REFERENCES

- Arendt, R.G. et al. , 1998, ApJ, 508, 74
- Brodd, S., Fixsen, D. J., Jensen, K. A., Mather, J. C., & Shafer, R. A. eds. 1997, *COBE/FIRAS Explanatory Supplement*, COBE Ref. Pub. No. 97-C (Greenbelt, MD: NASA/GSFC), available in electronic form from the NSSDC.
- Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icarus, 40, 1
- Clarke, F.O., et al. , 1993, Astronomical Journal, 105, 976
- Cox, A.N., ed, 2000, "Allen's Astrophysical Quantities" (New York: Springer-Verlag), p.293
- Cremonese, G., Fulle, M., Marzari, F., & Vanzani, V. 1997, A&A, 324, 770
- Draine, B.T. & Lee, H.M. 1984, ApJ, 325, 89
- Fixsen, D.J. et al. , 1996, ApJ, 473, 576
- Fixsen, D.J. et al. , 1997, ApJ, 490, 482
- Fixsen, D.J. et al. , 1998, ApJ, 508, 123
- Grün, E., et al. , 1985, Icarus, 62, 244
- Grün, E., 1993, Asteroids, Comets, Meteors, 160, 367
- Harper, D.A., Loewenstein, R.F. & Davidson, J.A., 1984, ApJ, 285, 808
- Hauser, M. G., Kelsall, T., Leisawitz, D., & Weiland, J. eds. 1997, *COBE/DIRBE Explanatory Supplement*, COBE Ref. Pub. No. 97-A (Greenbelt, MD: NASA/GSFC), available in electronic form from the NSSDC.
- Hauser, M.G. et al. , 1984, ApJ, 278, L15
- Hauser, M.G. et al. , 1998, ApJ, 508, 25
- Kelsall, T. et al. , 1998, ApJ, 508, 44
- Reach W.T., 1988, ApJ, 335, 468
- Leinert, C., Richter, E., Pitz, E., & Planck, B. 1981, A&A, 103, 177
- Leinert, C. 1996, in "Unveiling the Cosmic Infrared Background", ed. E. Dwek, AIP Proc. 348 (AIP: NY), p. 53
- Liou, J.C. & Zook, H.A., 1996, Icarus, 123, 491
- Liou, J.C., Zook, H.A. & Dermott, S.F., 1996, Icarus, 124, 429
- Mann, I., Grün, E. & Wilck, M., 1996, Icarus, 120, 399
- Mather, J. C. et al. , 1999, ApJ, 512, 511
- Reach, W.T. 1997, in Diffuse Infrared Radiation and the IRTS, eds. H. Okuda, T. Matsumoto, & T. L. Roellig, ASP Conf. Ser. Vol. 124 (ASP: San Francisco), p. 33
- Rouleau, F., & Martin, P.G., 1991, ApJ, 377, 526

Schlegel, D. J., Finkbeiner, D. P. & Davis, M., 1998, ApJ, 500, 525S

Vrtilek, J. M., & Hauser, M. G. 1995, ApJ, 455, 677

Fig. 1.— The decomposition of the sky into its different emission components: the 10 to 1000 μm annually-averaged spectra of the cosmic microwave background (dash-dot-dot-dot), the cosmic IR background (dash-dot), the ISM (dashed and *) and the zodiacal emission (solid and +).

Fig. 2.— The 10 to 1000 μm annually-averaged spectrum of the zodiacal dust cloud normalized to that of a 240 K blackbody. Diamonds represent the DIRBE data, and the solid line the FIRAS spectrum. At wavelengths below $\sim 150 \mu\text{m}$ the ZD spectrum is that of a graybody with an optical depth of $\sim 3 \times 10^{-7}$. At longer wavelengths the dust emissivity falls off as λ^{-2} .

Fig. 3.— The inferred size distribution of the zodiacal dust particles, assuming the ZD cloud consists of pure silicate dust. The size distribution falls off as $a^{-3.6}$ at large radii, and rises as $a^{1.4}$ at radii below the peak.

Fig. 4.— Left panels: Plots of χ^2 for the different model parameters (see §3 for more detail); Right panels: Contour plots of χ^2 showing the correlation between the different model parameters. The plots show that the covariance is modest.

Fig. 5.— The best-fitting model spectrum of the ZD cloud, consisting of pure silicate grains, is compared to the observations.

Table 1. Physical Characteristic of the Zodiacal Dust Cloud

Cloud composition	$T(0)$ (K)	a_b (μm)	$\langle m \rangle$ (ng)	n_0 (10^{-9} m^{-3})	M_z (Eg)
Silicate	274 ± 10	32 ± 2	7.6	22	8
Graphite	280 ± 10	20 ± 2	154	1.6	11
Amorphous carbon	280 ± 10	14 ± 2	6	1.2	3.4









